Global Warming - Just Hot Air?

by David S. Chapman

Abstract

We know from weather station records that Earth's surface temperature has increased on average by 0.6 degrees C in the last 100 years. The 1990s have been the warmest decade on record. Over the same period, global sea level has increased by 10-20 cm. We know also that planet Earth has an atmosphere that creates a natural greenhouse effect, keeping our surface warmer than it would otherwise be. Human activities are substantially increasing the atmospheric concentrations of greenhouse gases, principally carbon dioxide and methane, to levels far above those that have existed for the past 200,000 years.

We do not know, on the other hand, all the details of our complex climate system sufficiently well to predict the exact consequence of greenhouse gas increases on global temperature. Should we wait for greater certainty about global warming or should we take steps immediately to stabilize possible climate change?

Global trends suggest that allowing "business as usual" is a risky path. World population is now 6 billion and will likely rise to 10 billion in the lifetimes of our children. Much of the population growth will be in developing countries with a natural desire for an increased standard of living. That living standard increase, according to current examples, comes with increases in per capita energy consumption. Because 90% of society’s energy presently is produced by burning fossil fuels, the inevitable population increase and drive towards higher standard of living simultaneously aggravates the enhanced greenhouse gas condition and, with it, global warming.

There is an alternate path. We could unleash our engineering, economic, and political entrepreneurs to improve energy conservation and efficiency and move us towards greater use of renewable energy sources. Technology and training in energy efficiency and use of non-polluting fuels could allow developing nations to skip the carbon intensive, energy - production stage of industrialization. Such a path would simultaneously reduce excessive consumption in developed countries and provide conditions that would bring worldwide population growth under control. Global warming may be the "smoke alarm" that pushes us to action.

Global Warming - Just Hot Air?

What do we know? What do we not know?

What can we do? What should we do?

Life has existed on planet Earth for about four billion years. In that time, climate has swung between ice ages and warm periods. But generally, Earth's atmosphere has been in chemical balance, its composition changing slowly in response to changes in geology and life on the planet's surface. Now, growing population and the by-products of civilization are upsetting this balance.

In 1995, after years of study, the Intergovernmental Panel on Climate Change (IPCC) reached the cautious conclusion that is worth stating in full. "Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural climate variability, and because there are uncertainties in key factors. These include the magnitude and patterns of long term natural variability and the time-evolving pattern of forcing by, and response to, changes in the concentrations of greenhouse gases and aerosols, and land surface changes. Nevertheless, the balance of evidence suggests a discernible human influence on global climate." For the first time in the planet's history, humans are significant agents of global change.

Global warming, the gradual increase over decades of the surface temperature of the Earth, is one aspect of global climate change. Not everyone agrees, however, that the globe is warming or, if warming is occurring, that humans are to blame. Or that climate change is bad. Skeptics argue that it is premature to take action to slow or reverse global warming. Such action may have great costs. A global accord called the Kyoto Agreement commits the governments of the world to action but is hotly contested by opponents. Information and misinformation daily deluge us. In many ways "we are drowning in information while starving for wisdom."

It is therefore timely to consider four important questions about global climate change in general and global warming in particular. What do we know? What do we not know?

What can we do? What should we do? In this presentation, I intend to show how we know that the phenomenon we call global warming is real and cite evidence suggesting that an increase in greenhouse gas concentrations in our atmosphere is at least partly causing the warming. Uncertainties about the future course of global warming center on the role of two important climate feedback mechanisms and their influence on surface temperature. I conclude by viewing the choices that are available to deal with the problem and suggest a preferred action.

What do we know?

Warming in this century. We have evidence from three independent sets of measurements that widespread warming of the Earth's surface has occurred in this century. They are surface air temperature measurements, sea level changes, and temperature profiles in boreholes.

Direct temperature measurements at weather stations suggest that the surface of Earth has warmed, on average, by 0.6 ^{o}C (1 ^{o}F) in the last 100 years. The evidence comes from temperatures routinely measured and reported daily for thousands of weather stations around the world both on land and at sea. Daily temperatures are combined to produce average weekly, monthly, and annual temperatures. We can track how the average annual temperature changes from year to year.

A summary picture of all those temperature measurements for the last 140 years is shown in Figure 1. Measurements from the weather stations have been combined to produce an average temperature for the entire globe each year. Between 1860 and 1910 the global surface temperature fluctuated between 13.4 and 13.6 ^{o}C with no obvious trend. Temperatures rose rapidly between 1910 and 1945, stabilized for 3 decades and then rose again dramatically after 1975.

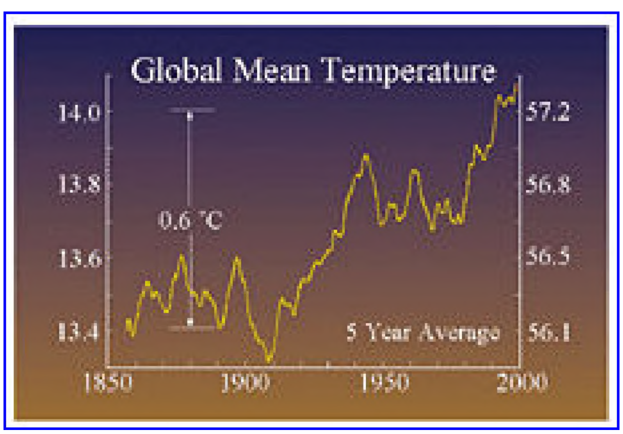

Figure 1. **Global warming revealed**. Air temperature measured at weather stations on continents and sea temperature measured along ship tracks on the oceans are combined to produce a global mean temperature each year. This 150-year time series constitutes the direct, instrumental record of global warming..

The 1990s are significantly warmer than the 1980s or any previous decade in the century. The global mean temperature has increased by 0.1 $_{o}$C per decade for the last twenty years with 1998 being the warmest year on record. There is little room to dispute the clear increase in global mean temperature of 0.6 $_{o}$C in this century.

It is important to say what Figure 1 is and what it is not. Precisely, it is a graph of the average temperature at Earth's surface on land and at sea. On land, air temperatures are measured at weather stations by thermometers mounted 1-2 meters above the ground surface. At sea, the temperature of the sea surface water is measured along ship tracks. Much effort has been spent in correcting raw measurements to compensate for changing technology over time such as the change from mercury thermometers to digital electronic thermometers, and for the changing the location of weather stations. Statistical methods have been used to close gaps in the record. The effect of large population centers, called the "urban heat island effect", has also been calculated; it accounts for less than 15% of this century's global warming.

Figure 1 is also a picture of the change in average temperature for the entire planet. But not all parts of the globe exhibit the same amount of warming. Low latitude regions generally have warmed less, high latitude regions more. Some areas have even exhibited slight cooling over the same time period. Furthermore, warming is not uniform in time. All regions of the globe have experienced years of cooler temperatures imbedded within the warming trend. The irregularity of warming in both time and space merely indicates a chaotic component to climate change.

A confirmation of this century's warming trend comes from a completely independent set of measurements. Sea level is rising (Figure 2). The volume of water in oceans is increasing because glaciers and ice caps are melting and because water already in the oceans is expanding as it is being heated. As with temperature observations, sea level is measured at many sites each day. Daily fluctuations,

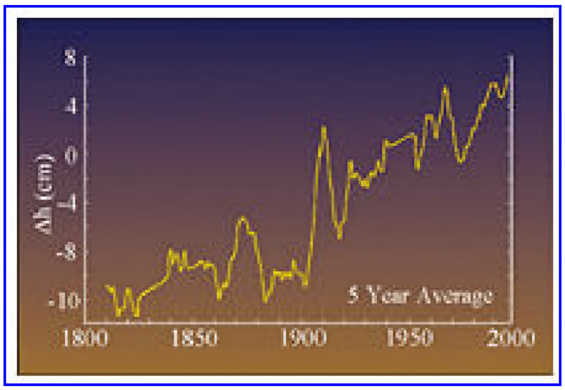

Figure 2. Sea level is changing. Observing stations from around the world report year-to-year changes in sea level. The reports are combined to produce a global average time series. The year 1976 is arbitrarily chosen as zero for display purpose.

caused principally by tides and storms, are averaged out and the slow changes over time can be charted. Mean sea level was nearly 8 cm below the 1976 level for the last part of the 19th century (Figure 2) and since 1976 has risen another 8 cm. In this century sea level has risen by 16 cm. It is rising at the rate of more than 1 mm per year.

Sea level changes, like global temperature changes, are not steady. Nor are the detailed changes entirely synchronous with surface temperatures. Thermal expansion of the water column tends to come later than the corresponding change in surface temperature and the detailed differences are highly affected by ocean currents. The irregularity in sea level rise is another indication of the complex natural world that we live in.

A third confirmation that Earth's surface has warmed in this century comes from an unlikely source, the solid ground below our feet. The ground retains records of previous temperatures, call them fossil temperatures, whose history can be traced back to the climates of recent time, back into previous centuries. This archive of past temperatures is accessed simply by lowering a sensitive thermometer in a borehole to obtain a profile of temperature with depth below the surface.

If the surface of the earth warms or cools, the warming or cooling event propagates slowly downwards into the subsurface. The process takes tens to hundreds of years. Figure 3 shows a simple example of sudden warming ΔT at some instant in time t_o (upper panel). Prior to that time, if the surface temperature has been held constant at temperature T_o, the subsurface temperature field (lower right panel) would have adjusted to that temperature. By changing the surface temperature to T_1, that thermal equilibrium is upset and temperatures below the surface change slowly to regain thermal balance. If the temperature-depth profile in a borehole is measured at later time t_1 or t_2, the shape of the profile reveals both the magnitude and the timing of the surface temperature change.

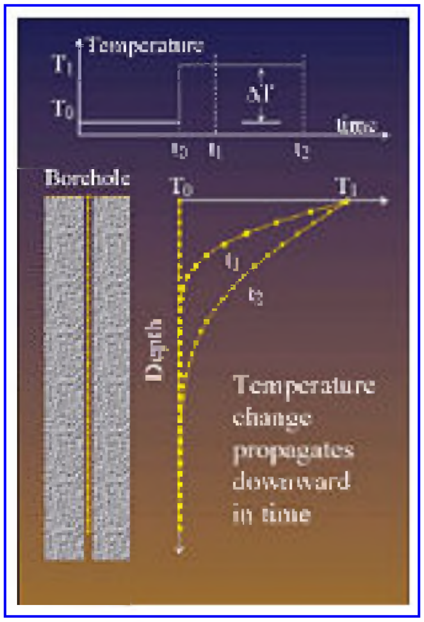

Figure 3. Climate change viewed from underground. A hypothetical change in temperature (DT) at Earth's surface at a particular time to(top) results in a characteristic pattern of underground temperatures that can be measured in a borehole (bottom left). Temperature-depth profiles (bottom right) measured at times t1 and t2 after a warming event display a diagnostic hook towards higher temperatures near the surface. The hook moves downward in time. Borehole temperature measurements can be analyzed to indicate how much warming or cooling has taken place, and when.

The process is analogous to sticking a poker in a fire. The end of the poker heats quickly, yet the handle remains cool. In time, heat is conducted down the metal rod, and eventually the handle may become too hot to hold. If the hot end of the poker is subsequently plunged into a bucket of cold water, a wave of cooling will follow the wave of heating down the length of the poker. The history of heating and cooling of the poker is revealed by the temperature profile along the poker. In the same way, temperature fluctuations at the surface of the earth propagate downward into the crustal rock. And this history of changing climate is recovered by measuring temperature profiles in boreholes. To read the profiles, of course, we must make correction for the expected steady temperature increase caused by heat flowing out of Earth's interior.

As surface temperature oscillations propagate downward, they become progressively smaller and die out. Shorter period fluctuations, however, attenuate more rapidly than do longer ones. Only longer-term variations penetrate to great depths. Seasonal oscillations penetrate only to about 15 meters before the signal is lost. A century long cycle in contrast, can be observed to about 150 meters and a millennial one to about 500 meters. In this way the earth selectively retains long-term trends and excludes short period excursions from the archive, an excellent trait for recording climate change. All changes in climate that have occurred in the past millennium are theoretically imprinted in the uppermost 500 meters of the crust, a depth easily attainable by inexpensive drilling.

Already several geothermal data sets from North America have been analyzed for evidence of surface temperature changes (Figure 4, upper panel). Investigations in the Alaskan Arctic by Arthur Lachenbruch and his colleagues at the US Geological Survey provided dramatic evidence of warming. Temperature profiles from wells spread across 500 kilometers of northern Alaska show anomalous warming of 2-5 degrees C in the upper 100 to 150 meters of the permafrost and rock. The depth where warming is evident shows that surface climate change in Alaska had a 20th Century onset. Borehole temperature profiles in Eastern

Canada document a less dramatic but equally clear warming of more than 1.0 degrees C. Nebraska sites and Utah sites both exhibit warming of about 0.5 to 1.0 degrees C, also starting around the turn of this century. The geographic variation in warming seen in weather station data, greater at high latitudes and lesser at low latitudes, is mimicked in the geothermal data.

The geothermal analysis provides more information than a simple confirmation of 20th century warming. For each site it is possible to infer an 18th-19th Century baseline temperature that existed prior to any instrumental record. This is a critical period of time that connects

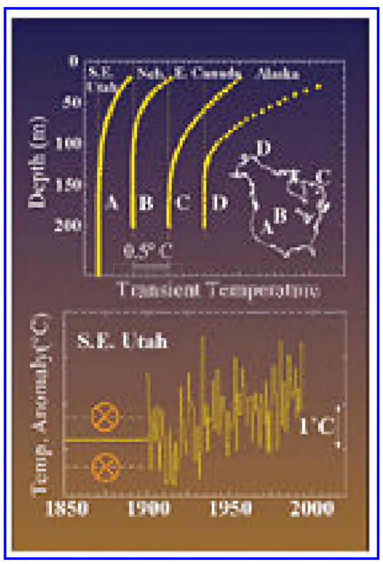

Figure 4. Borehole temperatures confirm widespread warming in North America. Borehole temperature profiles from sites in North America (top) show diagnostic hooks towards warmer temperatures within the uppermost 100-150 meters near the surface. The profiles suggest substantial warming in the last century from 0.6 degrees C in southeast Utah to more than 2 degrees C in Alaska. Curves are arbitrarily offset for display purposes. Borehole temperatures also extend the record of climate change to critical times prior to weather station instrumental records (bottom). A 19th Century baseline temperature can be found for each area that, when combined with the instrumental weather station data, reproduces the regional borehole temperature profile.

the start of the industrial revolution to the present century. Weather station temperature records (Figure 4, lower panel) are used as a forcing function to compute a predicted subsurface temperature profile. But an average temperature prior to weather station operation is required for the calculation. And different baseline temperatures result in very different synthetic borehole temperature profiles. The predicted borehole temperature profile based on the measured weather data and various assumed baseline temperatures is compared to the measured borehole profile and the assumed baseline temperature is adjusted until the prediction agrees with the measurements. Solid lines in Figure 4 (upper panel) show the good agreement between prediction and observation, indicating that borehole temperatures are indeed a faithful recorder of climate change. The preferred baseline temperature for southeast Utah (Figure 4, lower panel) is clearly about 0.8 degrees C cooler than temperatures in the 1990s. Such analyses have been done for many sites around the world and provide strong evidence that 20th Century warming is significant and not merely a return to a warm period that existed 100 to 200 years ago.

The greenhouse effect

What controls planetary surface temperatures and their changes through time? We know that an energy balance determines Earth’s surface temperature. Incoming solar radiation is balanced by outgoing thermal radiation from the planet. Incoming solar radiation depends on the solar output and the distance of the planet from the sun, and is independent of Earth's surface temperature. Outgoing thermal radiation, on the other hand, has a very strong 4th power dependency on Earth’s surface temperature. If planets were born with a cold surface they would quickly warm because the incoming radiation would exceed outgoing radiation. Surface temperature, and hence outgoing radiation, would increase until a balance is reached. On the other hand, planets born hot would soon have surfaces relatively cool with respect to their cores, because of the high rate of heat loss due to radiation. In a relatively short time, the surface temperature would depend more on the radiation equilibrium than on the internal core temperature of the planet.

Consider the hypothetical case of Earth with an atmosphere composed only of nitrogen and oxygen, molecules that do not absorb outgoing thermal radiation, but missing the greenhouse gases water vapor, carbon dioxide, and methane. The energy balance would control the Earth's temperature to be -6 degrees C, rendering much of the planet frozen. Adding greenhouse gases in their natural abundance traps some of the outgoing thermal radiation and reestablishes a new energy balance with a surface temperature of +15 degrees C. This 21 degrees C of warming is referred as the natural or beneficial greenhouse effect.

Satellite observations of "earthlight" confirm details of the greenhouse effect for Earth (Figure 5). Earthlight is the outgoing thermal radiation from Earth. Without an atmosphere to absorb radiation the radiance is mapped by a smooth curve called the spectrum which peaks at a wavelength of 20 micrometers, nearly 40 times longer than the wavelength of incoming visible light. But not all of the radiation gets out. The shaded regions of Figure 5 show how much radiation is absorbed by greenhouse gases water (55%), carbon dioxide (30%) and methane (20%). Other minor greenhouse gases account for the remaining absorbed radiation.

Although most of the natural greenhouse effect is due to water vapor, the amount of water in the atmosphere is

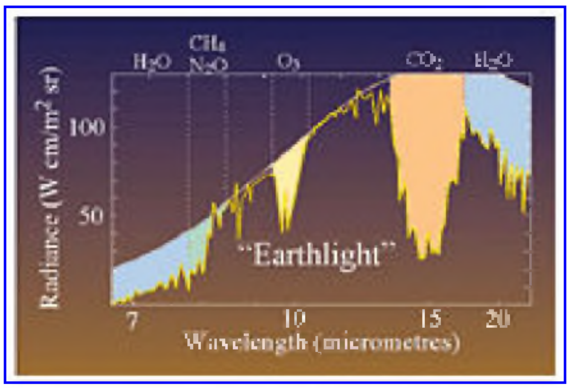

Figure 5. Earthlight confirms greenhouse effect. Thermal radiation emitted from the Earth's surface and atmosphere observed from a satellite instrument looking down at Earth (irregular line). In the absence of a greenhouse effect, the radiance would follow the solid smooth curve. Shaded regions represent the radiation absorbed by greenhouse gases in diagnostic wavelength bands. Units of radiance are watts per square meter per steradian per wavenumber. [After Houghton, 1997].

changing relatively little because of human activities. The greenhouse gases that are changing due to human activities are carbon dioxide, methane, nitrous oxides, ozone and CFCs. Of these, the most important human-derived greenhouse gas is carbon dioxide.

Each year, the burning of fossil fuels adds about 5.4 billion tons of carbon to the atmosphere. Deforestation accounts for another 1.6 billion tons by reducing the storage of carbon by trees. The result is that the atmospheric level of carbon dioxide has increased 30% from 280 to 370 parts per million by volume (ppmv) since 1860 (Figure 6). The carbon dioxide buildup in the atmosphere has been measured instrumentally since 1959 at an observatory near the summit of Mauna Loa in Hawaii. Each year, atmospheric carbon dioxide rises and falls by almost 6 ppmv signaling the growing and dormant seasons for plants (Figure 6, inset). But each year the annual maximum and minimum increases by about 1.5 ppmv. This growth of carbon dioxide concentration is particularly problematic because the gas has an average lifetime of 100-150 years in the atmosphere being depleted mainly by dissolution in the oceans over time. If we were to decrease our input of carbon dioxide dramatically today, the effects of the present concentration of carbon dioxide would still be felt for another 150 years.

A pictorial case, relating global warming to increases in greenhouse gas concentration is made in Figure 7.

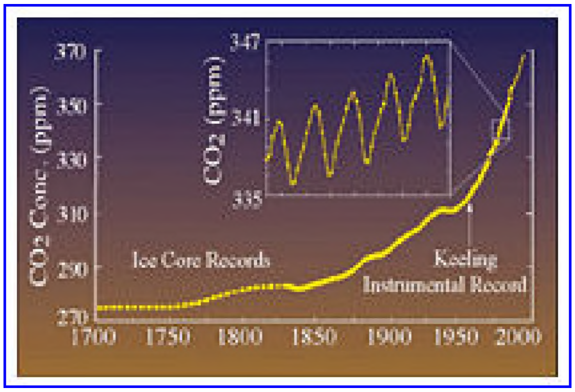

Figure 6. Rise in atmospheric carbon dioxide. The concentration of carbon dioxide in Earth's atmosphere has increased steadily from 270 to 370 ppm since 1700. Early data come from gas bubbles trapped in ice. Since 1959, carbon dioxide concentration has been measured at observatories in Hawaii and elsewhere. Recent measurements show uptake and release of carbon dioxide with seasons (inset) superimposed on the steady global increase.

Measurement of carbon dioxide and methane concentration in bubbles trapped in old ice in Greenland and Antarctica establish baseline greenhouse

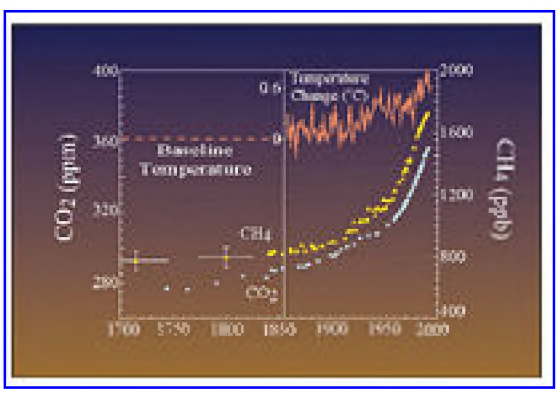

Figure 7. Global warming linked to greenhouse gases? A comparison of global temperature increase with the increases in important greenhouse gases carbon dioxide and methane, both related to human activity, suggests a link between global warming and the enhanced greenhouse effect. Coincident increases, however, do not prove cause and effect.

gas concentrations for the period 1700 to 1850. Analysis of borehole temperatures fixes the surface baseline temperature. As greenhouse gas concentrations increase in the 20th century, so do surface temperatures.

What do we not know?

It is clear from weather station data, from sea level rise, and from borehole temperatures that Earth's surface has warmed significantly in this century. And the most likely explanation of the warming is an enhanced greenhouse effect. Why then, is there reluctance among sectors of our society to accept the concept of global warming and to agree to a reduction in atmospheric greenhouse gas emissions? It may be because those sectors feel that other explanations for global warming, such as possible variations in solar radiation, or natural variations in Earth's temperature independent of human actions are responsible. It is also possible that the complexity in Earth's climate system is exceeded by the complexity in human behavior and reaction to change. But it also may be that scientists are still uncertain about all aspects of global warming. Whereas scientific uncertainty is a fact of life for scientists, it is a difficult concept for policy makers and ammunition for skeptics with varying agendas.

A helpful analysis of the uncertainties in projections of the magnitude of global warming we can expect in the future, and changes in related climate effects, was recently provided by Jerry Mahlman of Princeton

University. He separates issues that scientists feel very confident about from those with greater uncertainty.

There should be little debate, in Mahlman's view, on the following aspects of climate change: (1) atmospheric abundance of greenhouse gases are increasing because of human activity, (2) the presence of greenhouse gases leads to heating at the Earth's surface, (3) carbon dioxide buildup is particularly serious because it remains in the atmosphere for decades to centuries, (4) buildup of aerosols, anthropogenic or natural, inhibits incoming solar radiation and thus tends to offset warming, (5) over the past century Earth's surface has warmed by about 0.6 degrees C, and (6) the global mean amount of water vapor in the atmosphere will increase with the global mean temperature.

Other projections are less certain but have a greater than nine out of ten chance of being true. Mahlman projects that: (1) the 20th century global warming is consistent with model predictions of expected greenhouse warming, (2) doubling of carbon dioxide from 270 to 540 ppmv will lead to a total warming of 1.5 to 4.5 degrees C, (3) sea level could rise by 25 to 75 cm by the year 2100 caused mainly by thermal expansion of sea water. Melting of ice sheets could lead to a further sea level rise. (4) Higher latitudes of the Northern Hemisphere will experience temperature changes much higher than the global average increase.

The range in several of the above projections is caused by uncertainties in modeling feedback in the climate system. Feedback is a system response whereby a small change in a particular direction may be amplified (positive feedback) or attenuated (negative feedback). Increased water vapor in the atmosphere from a warmer climate, for example, produces a positive feedback. Because water vapor is a greenhouse gas, increased evaporation of water enhances the greenhouse effect, producing even greater evaporation. Ice sheet reflectivity is another positive feedback system. Snow and ice reflect solar radiation back into space. If a warming episode melts a significant area of ice, less sunlight is reflected away, leading to more warming and eventually more ice melting.

The cloud-radiation feedback system is much more complicated. Clouds sometime cool Earth by blocking incoming solar radiation but they can also act as a thermal blanket and warm Earth by absorbing thermal radiation emitted from the surface. There is continuing debate as to whether the net feedback of many different cloud types, varying through space and time, is positive or negative. Oceans also have complex but important influence on climate. Oceans provide most of the planet's atmospheric water, they modulate weather because of a very large heat capacity, and they redistribute heat around the globe through their internal circulation such as the Gulf Stream. Any accurate simulation of climate change must include ocean structure and dynamics. The incomplete understanding of these two feedback systems hampers our ability to predict the exact timing, magnitude and regional patterns of climate change. The complexity of the systems means that we cannot rule out surprises.

Much work is in progress sharpening the global warming picture and looking for distinctive fingerprints of significant climate change. But neither the fuzziness in the picture nor elements of genuine scientific uncertainty in the picture should be confused with the global warming problem not existing.

What can we do?

Are there methods, beyond reducing the emission of greenhouse gases, to engineer a cooler planet? Proponents of geoengineering who would control nature on a large scale say yes. One of the most interesting proposals is known as the ocean "geritol solution." An oceanographer, the late John Martin, theorized that adding iron to the ocean would fertilize the waters, stimulating the growth of microscopic marine plants or phytoplankton which use carbon dioxide to make food. Two experiments in 1993 and 1995 confirmed Martin's hypothesis. Liquid iron dissolved in seawater was spread over a 25 square mile section of the Pacific Ocean. After several days clumps of phytoplankton filled the fertilized patch. Some species increased to 85 times their normal number, consuming hundreds of tons of carbon dioxide in the process.

Another simple and more practical way to combat global warming is to plant more trees. Forests sequester a large amount of carbon in their leaves and soil. They also stabilize soil, and restore wildlife. But planting enough trees to completely offset global warming would require vast regions and compete for agricultural lands needed to feed expanding populations.

There are also a number of innovative geoengineering suggestions that might be considered as imaginative techno-fixes, impractical but interesting. There is the "pollution solution", a proposal to inject sulfur into the stratosphere where it would block incoming sunlight and thus produce surface cooling. Volcanoes such as Mt. Pinatubo performed such an experiment and cooled the planet by 0.25 degrees C for the three years that sulfur remained in the stratosphere. Other "sunscreen" schemes envision sending mylar balloons or thousands of mirrors into orbit around Earth to block sunlight. The amount of solar radiation bounced back into space could also be increased by changing the reflectivity of land and ocean surfaces. Oceans could be coaxed to absorb more atmospheric carbon dioxide by increasing its alkalinity. None of these geoengineering solutions, however, are cost effective, and many have other environmental drawbacks.

We can also take action to reduce the emission of greenhouse gases. Such action would include requiring that an increasing percentage of future electricity production and motor fuels should come from non-fossil fuel resources, establishing stringent emission standards for power plants, developing and marketing high fuel efficiency automobiles, and providing financial incentives for energy efficiency throughout industry and the home. But just to stabilize carbon dioxide at its current atmospheric levels, for example, we would have to halve emissions immediately. The debate as to whether the possible economic costs of reducing greenhouse gas emissions are too great is heated. Fossil fuel companies are divided on suggested action. An Exxon special report in December 1997 that is titled "The Global Debate over Global Warming - Uncertain Science, Real Costs" recommends not taking action to reduce fossil fuel consumption without further study. British Petroleum, on the other hand, has taken an official stand on "being part of the solution and not part of the perceived problem."

What should we do?

A strong argument can be made that "business as usual" in terms of greenhouse emissions is a dangerous course to follow. That argument is based on the reality of three issues: population growth, energy consumption related to standard of living, and energy production.

Human population is now six billion (Figure 8). In 1780 AD the population was one billion. Just 150 years later, in 1930, the population had doubled to two billion. The last doubling, from three to six billion, took only 45 years. It now takes only 11 years to add a billion people to the Earth's population, although there are indications that the growth rate is slowing. But because of the age distribution of many countries, population momentum will carry Earth's human population with certainty into the 10-12 billion range. The inset of Figure 8 illustrates the predicament. Percentages of the country's population are shown for each 5-year age group for two countries. In rapid growth countries such as Kenya about 20% of the population is between ages 0 to 5. Nearly half the population is in the age range 0-15. It is the childbearing potential of this section of the population that propels population momentum and results in growth projections for the globe. In slow growth countries such as the USA, only 7% of the population are in the age bracket 0-5, and there are as many Americans in the age bracket 40-45 as in the 0-5 year age group. But rapid growth countries still outnumber slow growth countries and so global population will still climb even as birth rates decline.

Now combine inevitable population growth with aspirations of people world wide for a higher standard of living.

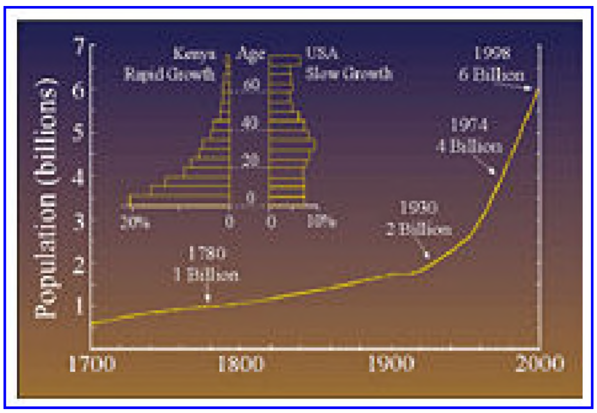

Figure 8. The population bomb. Human population traced from 1700 to the present. The Earth's population, about one billion at the time of the industrial revolution, will exceed 6 billion in October, 1999. Population distributions, in five-year age brackets, are shown for rapid and slow growth countries (inset). Because rapid growth countries exceed slow growth countries, and because of population momentum, human population is predicted to rise to 10-12 billion before stabilizing.

One measure of quality of life, developed by the United Nations, is a Human Development Index (HDI). The HDI is based on life expectancy, educational level, and per capita gross domestic product. It is measured on a scale of 0 (poorest performance) to 1 (ideal performance).

Figure 9 shows dramatically that energy consumption plays a determining role in the achievement of standard of living (HDI). This influence is particularly acute in the early stages of development

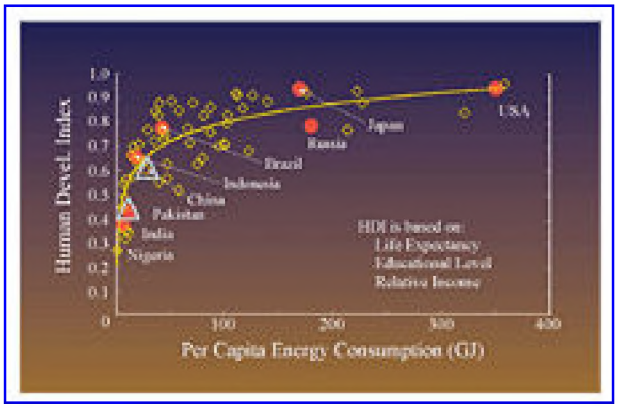

Figure 9. Energy consumption drives standard of living. The human development index (HDI) for individual countries, a measure of living standard, shows a strong dependence on per capita energy consumption. Energy units are Giga-Joules (1 GJ = 10^9 Joules). Different symbols indicate country populations of 500 million or more (triangles), 100 million to 500 million (circles) and less than 100 million (diamonds). As high-population countries such as Nigeria, India, Pakistan, China, and Indonesia increase their standard of living, the energy consumption path they choose will have major implications on global energy demands.

in which the vast majority of the world's people find themselves. China and India (triangle symbols, Figure 9), the two most populous nations on Earth which together comprise more than one third of the world's populations, have per capita energy consumption of 10 and 40 GJ (1 GJ =10^9 Joules) respectively. If these two countries increase their standard of living by following the curve in Figure 9, global consumption of energy will increase dramatically.

The influence of per capita energy consumption on the HDI begins to decline at about 50-100 GJ per capita. Thereafter, even with a trebling in energy consumption, the HDI does not significantly increase. A level of 100 GJ per capita could be sufficient to support a reasonable level of development if it could be used efficiently. The three countries with the highest per capita energy consumption (Figure 9) are Canada, USA, and Kuwait; these three countries have per capita energy appetites of 360, 350, and 320 GJ respectively. How are these increasing demands for energy being met? Fossil fuels (coal, oil, and natural gas) account for 90% of energy consumption in the world today (Figure 10). That percentage has decreased only slightly since 1970 while the annual total energy consumption has increased 30% from 250 to nearly 400 Exa-Joules (1 Exa-Joule = 10^18 Joules of energy).

When taken together, the inevitable growth of human population combined with individuals and societies having a legitimate desire to raise standard of living by consuming more energy and the present reliance on fossil fuels for energy, the prognosis for more atmospheric carbon

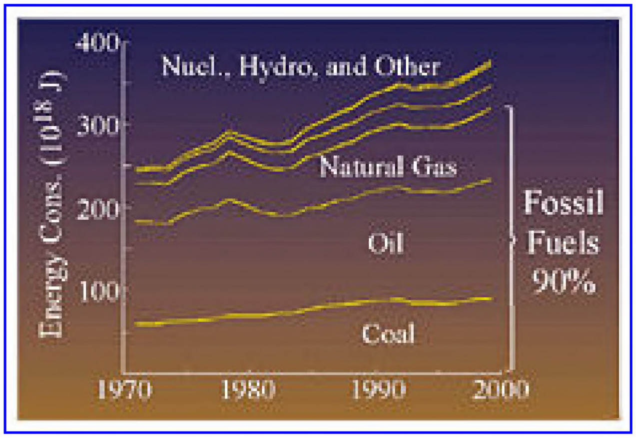

Figure 10. Global energy consumption. Global energy demand is growing at about 1.3 percent per year, roughly keeping pace with population growth. About ninety percent of human energy demand is satisfied by burning fossil fuels, releasing increasing amounts of carbon dioxide into the atmosphere and contributing to the enhanced greenhouse effect.

dioxide emissions and likely accelerated global warming is bleak. Atmospheric carbon dioxide concentration will likely be more than 700 ppmv by year 2100, far beyond the natural range 200-300 ppmv that has characterized the Earth over the last 150,000 years. State-of-the-art climate models suggest that these elevated carbon dioxide levels will lead to an increase in global temperature of about 2 oC during the next century, a rate of climate change not known in recent geologic history.

There are other alternatives. Some require global commitment, others require public leadership, and yet others rely on individual actions. The most general solution for the global warming dilemma requires changing the future projections of the curves shown in figures 8, 9, and 10. First, population growth must be brought under control (Figure 8) so that the word's population stabilizes at 10 billion or fewer people, not more. Second, both developed and developing countries should aim to achieve a high standard of living in the sustainable per capita energy consumption range of 100-150 GJ (Figure 9). Canada and the USA should reduce their excessive energy consumption. Developing countries should try to maximize their HDI at the least growth in energy consumption, using models other than the USA and Canada for development. Third, creative talents of engineers and scientists need to be challenged into improved energy efficiency and fuel switching to reduce our dependency on fossil fuels (Figure 10).

Public leadership is important. To achieve the economic potential of improved energy efficiency and fuel switching, governments should provide a combination of targets and timetables, efficiency regulation and an array of market-based incentives that encourage businesses to make the necessary investments to reduce carbon dioxide emissions. Such measures could include: mandating high energy-efficiency standards, retrofitting buildings to conserve energy, reducing subsidies that distort energy prices, developing market-based measures such as tradable emissions permits, encouraging fuel switching to less carbon intensive fuels, developing renewable energy sources, working with automakers to encourage use of more energy efficient vehicles, and assisting municipalities with planning that minimizes vehicle use. . All these measures will have greatest effect if implemented in a timely manner. Some studies indicate that policies to reduce greenhouse gas emissions produce economic benefits greater than their costs. Policies encouraging energy efficient processes and renewable energy technologies are a bridge to the knowledge-based economies of the 21st century.

Individuals can also make a difference. Use a fuel-efficient car and drive less, live closer to work, walk or ride a bicycle. Buy local and seasonal goods to reduce consumption of energy for transportation. . Make sure your house is well sealed and insulated to reduce heating in the winter and cooling in the summer. Use compact fluorescent light bulbs and energy-efficient appliances. Plant trees and shrubs. Compost and recycle. Through the democratic process, encourage your elected officials to deliver policies that properly take the environment into account. After all, if people can cause global warming, people can stop it.

The global warming debate, finally, may force us to develop a more global and less insular perspective of planet Earth's future. Sir John Houghton, co-chairman of the Scientific Assessment Working Group of the IPCC, sees global warming as just one of four global environmental issues that needs addressing. The first issue is global population growth and the demands of the 90 million new people added each year for food, energy, and work to generate the means of livelihood. The growing demand for energy will pump increasing amounts of carbon dioxide into the air. The second global issue is that of poverty and the increasing disparity in wealth between the developed and the developing world. In 1960 the ratio of income between the richest 20% of the world's population and the poorest 20% was 30 to 1. By 1991 that ratio had grown to 60 to 1. A third environmental issue is the consumption of resources including agricultural land and groundwater at unsustainable rates. We are affecting their use by future generations. The fourth issue is that of global security. Recent wars have been fought over oil and future wars over water are a distinct possibility. Climate change resulting in loss of land or resources would put additional tension into the global political arena.

The solution to these problems and issues are complex. The scales are global and the time scales are decades to centuries. The challenge, and overall goal, is appropriate environmental stewardship of the planet. Global warming may just be the alarm that brings us, albeit with much debate, to action.

Additional Reading and Browsing

1. Articles and books:

Broecker, W.S., Global warming on trial, Natural History, v. 4, p. 6-14, 1992.

Pollack, H. N., and D.S. Chapman, Underground records of changing climate, Scientific American, v. 268, no. 6, p. 44-50, 1993.

Lachenbruch, A. H., and B.V. Marshall, Changing climate: geothermal evidence from permafrost in the Alaskan Arctic, Science, v. 234, p. 689-696, 1986.

Houghton, J. T., Global Warming: the Complete Briefing, Cambridge University Press, pp. 251, 1997.

2. Web sites:

[NASA's Goddard Institute for Space Studies: http://www.giss.nasa.gov/](http://www.giss.nasa.gov/)

> This site has extensive information, images, and data sets available on climate change including data on mean sea level change, global temperature change, atmospheric greenhouse gas concentrations, and earth atmospheric radiance.

[IPCC Data Distribution Center: http://ipcc-ddc.cru.uea.ac.uk/](http://ipcc-ddc.cru.uea.ac.uk/)

> The Intergovernmental Panel on Climate Change (IPCC) established a data distribution center to facilitate the timely distribution of a consistent set of scenarios of changes in climate and related environmental and socio-economic factors for use in climate change impact assessments. The web site contains observed global climate data sets, socio-economic scenario information, and results from global

climate model experiments.

US Department of Energy — Energy Information Administration: http://www.eia.doe.gov/

US Department of Energy - Efficiency and Renewable Energy Network: http://www.eren.doe.gov/

Collections of world energy data for most countries. Detailed reports on each country are available that include such statistics as total and per capita energy consumption, carbon emissions, and energy production.

The David Suzuki Foundation: http://www.davidsuzuki.org/

An environmental and social action group based in Canada. The Suzuki Foundation publishes a number of global climate change reports focussed on a variety of topics related to global climatic change and humanities influence. Most are available on the web site. The foundation also advocates environmentally sensitive position in public policy and in the private sector.

United Nations Development Program: http://www.undp.org/

The UNDP collects statistics and funds programs related to socio-economic development around the world. In addition, they assist nations in implementing environmental and other policies related to socio-economic development. The UNDP's highest priority is the eradication of poverty world wide. Information available from this site includes economic indicators for countries around the world, Human Development Index (HDI) statistics, gender issues, and environmental policies worldwide.

A ticking population clock!: http://www.opr.princeton.edu/popclock/

This site features a "population clock" that continuously displays an estimate of the current world population. Additional links to other population web sites are also available at this site

Population Reference Bureau: http://www.prb.org/

UNDP Population Information Network (POPIN): http://www.undp.org/popin/

Zero Population Growth: http://www.zpg.org/

Data sets are available for the current and past populations of individual countries around the world, as well as age distributions in certain countries and regions.

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